$C^{13}(p,\gamma)N^{14}$ Reaction and the 9.17-, 7.03-, and 6.44-MeV States in N^{14}†

F. W. PROSSER, JR., R. W. KRONE, AND J. J. SINGH*
The University of Kansas, Lawrence, Kansas

(Received 25 September 1962)

A re-examination of the γ-ray decay of the 9.17-MeV state in N^{14}, reached at the 1.75-MeV resonance in the $C^{13}(p,\gamma)N^{14}$ reaction, has confirmed the shell-model assignments previously given to that state and the 7.03-MeV state. The observation of a weak transition to the 2.31-MeV state supports the positive parity assignment of the 9.17-MeV state. Angular distribution and correlation measurements indicate an amplitude ratio of f wave to p wave in the formation of the compound state of -0.70 ± 0.26 and $E2/M1$ amplitude ratios of -0.005 ± 0.020 and -0.6 ± 0.1 for the 9.17 → ground-state and 7.03 → ground-state transitions, respectively. A slight preference for a positive parity assignment for the 6.44-MeV state is found. The results, in general, are in good agreement with the calculations of Warburton and Pinkston. The alternative shell-model configurations suggested by them for the 6.44-MeV state are examined, but existing data are found to be inconclusive.

INTRODUCTION

THE properties of N^{14} have long prompted theoretical interest. A number of shell-model calculations have been made of the level spectrum and the electromagnetic transition rates to be expected in this nucleus.[1–4] A number of these states have been identified and their properties found to be in reasonable agreement with predictions.[4,5] Of particular interest and importance in the determination of the wave functions of the (p^{-2}) configuration[6] has been the location of the $(2+,0)$ state.[7] The 6.44-MeV state, reached by transitions from both the 9.17- and 10.43-MeV states,[8] has been shown to have spin 3[9–11]; it therefore cannot be the desired $(2+,0)$ state. A somewhat weaker branch has been observed to a state at 7.03-MeV excitation[5,11] and recent work by Rose has established that this decay is consistent with that expected from the $(2+,1)$ state to the $(2+,0)$ state.[5] Moreover, evidence has been presented that indicates that the 9.17- and 10.43-MeV states are both $(2+,1)$ states, each arising in part from the $p^8(s,d)$ as well as the (p^{-2}) configuration.[4] With this identification for these states the strong decay to the 6.44-MeV state can be understood if it is assumed to be the $(3+,0)$ state arising from the $p^8(s,d)$ configuration, expected in that range of excitation.

The strong excitation of the 6.44-MeV state in the $N^{14}(\alpha,\alpha')$ reaction[12] is, however, incompatible with that expected for a doubly excited state. Also, a relatively large partial width for f-wave formation of the 9.17-MeV state in the $C^{13}(p,\gamma)N^{14}$ reaction[10] has been found necessary to explain the angular distributions. In view of these discrepancies between theory and experiment, and in order to obtain a more precise determination of the amplitude ratios involved in the formation and decay of the compound state, it was decided to reinvestigate the angular distributions of the higher energy γ rays emitted in the decay of the 9.17-MeV state.

EXPERIMENTAL PROCEDURE

The targets were prepared by cracking CH_3I, enriched[13] to 46% C^{13}, on to 5-mil Au backing. These targets, when mounted in thermal contact with an air-cooled target post, were found capable of withstanding beam currents in excess of 10 μA without noticeable deterioration. The targets used to obtain the data reported here were determined to have thicknesses between 5 and 6 keV for 1.75-MeV protons. The yield of γ rays with energy higher than 6.5-MeV obtained at a bombarding energy 6 keV below the peak of the resonance was less than 2% of that obtained at the peak; therefore, it was not felt necessary to correct the data for off-resonance contributions to the pulse-height spectra.

The angular distributions were measured using a 5-in.-diam×5-in.-long NaI crystal whose front face was located 16 in. from the target. The pulse-height spectra from this crystal were recorded on an RCL 256 channel analyzer and the yields normalized to the counting rate measured by a fixed 3-in.-diam×3-in.-long NaI crystal with a bias set at 7.5 MeV. Pulse-height spectra were obtained at 5 angles between 0° and 90° and the symmetry of the apparatus checked by taking an additional spectrum at 120°.

† This work has been supported in part by the U. S. Atomic Energy Commission.

* Present address: William and Mary College, Williamsburg, Virginia.

1 D. R. Inglis, Rev. Mod. Phys. 25, 390 (1953).
2 J. P. Elliott, Phil. Mag. 1, 503 (1956).
3 W. M. Visscher and R. A. Ferrell, Phys. Rev. 107, 781 (1957).
4 E. K. Warburton and W. T. Pinkston, Phys. Rev. 118, 733 (1960), hereafter referred to as WP.
5 H. J. Rose, Nucl. Phys. 19, 113 (1960), and references given there.
6 Shell-model configurations are designated by the notation of WP, e.g., (p^{-2}) is $(1s)^4(1p)^{10}$.
7 The total angular momentum, parity, and isotopic spin of a state will be referred to in the notation $(J\Pi,T)$.
8 F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. 11, 1 (1959).
9 H. J. Rose, W. Trost, and F. Riess, Nucl. Phys. 12, 510 (1959).
10 R. E. Segel, J. W. Daughtry, and J. W. Olness, Phys. Rev. 123, 194 (1961).
11 R. W. Krone, J. J. Singh, and F. W. Prosser, Jr., Bull. Am. Phys. Soc. 4, 219 (1959) and Progress Report, AEC contract AT(11-1)-83 Project 6, 1960 (unpublished).
12 D. W. Miller, B. M. Carmichael, U. C. Gupta, V. K. Rasmussen, and M. B. Sampson, Phys. Rev. 101, 740 (1956).
13 The enriched $C^{13}H_3I$ was obtained from the Isomet Corporation, Palisades, New Jersey.

Two of the measurements of the angular correlation between the 2.73- and 6.44-MeV γ rays, previously reported in reference 11, have been re-analyzed and included in this report for completeness. These were obtained using two 3-in.-diam×3-in.-long NaI crystals, located with their faces 6 in. from the target, connected in a standard slow-fast coincidence circuit. The fast coincidence circuit had a resolving time 2τ of 35 nsec, for which the chance rate was found to be approximately 2% of the total coincidence counting rate. The energy criterion for the slow coincidence circuit was determined by a single-channel analyzer window set to accept the full energy peak of the 2.73-MeV γ ray. The coincidence counting rate was determined by summing the pulses occurring in channels between limits equivalent to energies of 4.0 and 7.0 MeV. The coincidence counting rate was normalized to that in a third monitor counter.

EXPERIMENTAL RESULTS

A spectrum, obtained at 45° in the same geometry used for the angular distributions, is shown in Fig. 1(a). An enlarged view of the data in the 5.5- to 7.5-MeV region, after subtraction of the tail of the 9.17-MeV γ ray, is shown in Fig. 1(b). It is clear from the absence of appreciable structure at 6.14 MeV, which could be attributed to F^{19} contamination of the target, that the structure at an energy of about 7 MeV does not arise from the $F^{19}(p,\alpha\gamma)O^{16}$ reaction, since the γ-ray spectrum from that reaction is invariably dominated by the 6.14-MeV transition.[8] Also, the 7.03-MeV transition has been reported previously.[5,11] The weak structure between the 6.44- and 7.03-MeV γ rays appeared in all spectra taken and attempts to carry out the decomposition of the spectrum without assuming a γ ray in this location were uniformly unsuccessful. Assuming this structure corresponds to a single transition, one obtains an energy of 6.85 ± 0.10 MeV. There are no known reasonable target contaminations other than F^{19} which give rise to a γ ray of this energy; therefore it must result from the $C^{13}(p,\gamma)N^{14}$ reaction. Since there are no known states in N^{14} at this excitation, the γ ray is assigned to a transition between the 9.17-MeV compound state and the (0+, 1) first excited state at 2.31 MeV. It will be shown later that both the relative

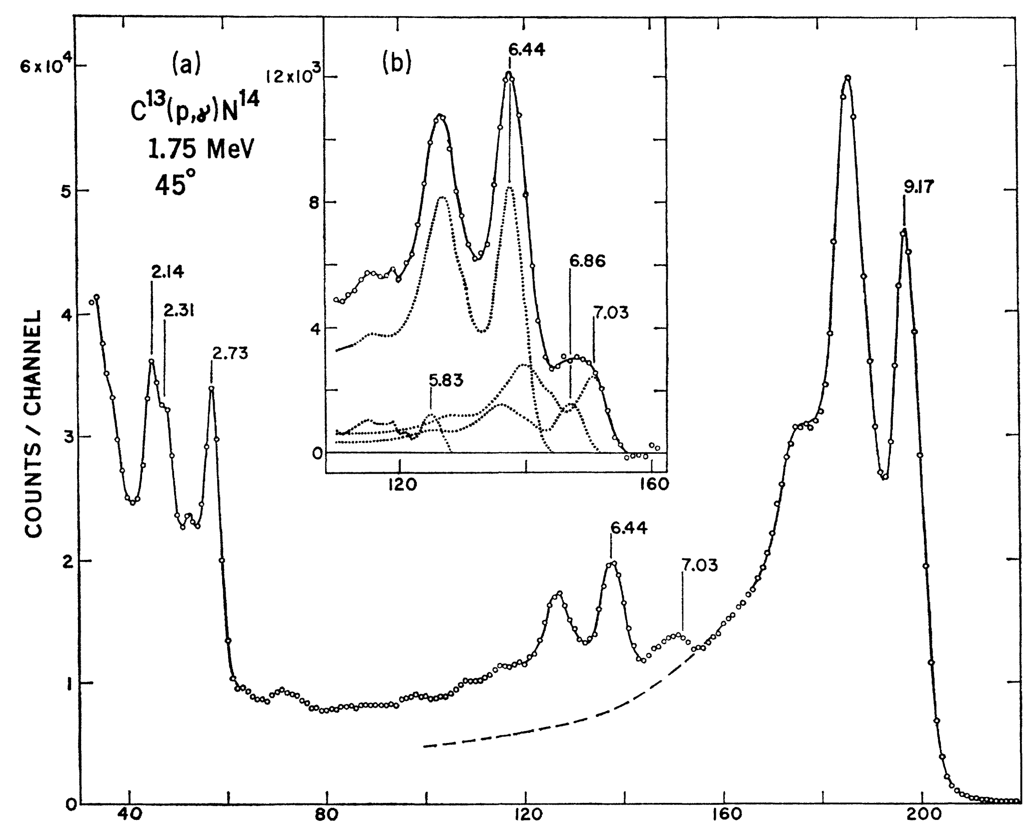

FIG. 1. Pulse-height spectrum. Various of the more prominent γ rays are indicated by their energies, given in MeV. The tail of the 9.17-MeV γ ray is indicated in (a) by the dashed line. Insert (b) is an enlargement of the region from about 5 MeV to 7.5 MeV, with the dashed curve subtracted. The decomposition of this portion of the spectrum into its component γ rays is indicated by the dotted lines; the solid curve passing approximately through the points is the sum of the four dotted curves. The size of the structure labeled 5.83 MeV is extremely sensitive to the assumed shape of the 6.44-MeV γ ray and is included only to indicate the remainder of the spectrum in this region after subtraction of the higher energy γ rays.

transition probability and the angular distribution are in reasonable agreement with this assignment.

The yield of each transition was determined at each angle by decomposition of the spectrum in the manner indicated in Fig. 1. The shapes of the pulse-height spectrum for each energy γ ray were determined by observation of known γ rays, e.g., 9.17 MeV from this reaction, 6.14 MeV from the $F^{19}(p,\alpha\gamma)$ reaction, 4.43 MeV from the $B^{11}(p,\gamma)$ reaction, etc., and interpolation of such features as the ratio of the heights of the full energy and single escape peaks. These shapes, once determined, were maintained constant throughout the analysis. The fact that the assumed shapes allowed a good fit, within statistics, at all angles served as a check. It is felt that this method, while admitting of some systematic error effecting relative transition probabilities, minimizes the error in the determination of the angular distributions. The area under each subtracted shape was integrated from the highest energy to $E_\gamma - 1.0$ MeV. The relative efficiency resulting from the use of only a portion of the full spectrum was calculated from the spectra of standard γ rays and the over-all detection efficiency to that of the 9.17-MeV γ ray was then determined in the standard manner. This correction was relatively small in all cases, requiring reductions of 15%, 13%, and 12% in the calculated yields of the 6.44-, 6.86-, and 7.14-MeV γ rays, respectively. The angular distributions obtained for the three γ rays, together with that of the 9.17-MeV γ ray, are shown in Figs. 2(a), (b), (c), and (d), and the least-squares fits are given in Table I. Similar measurements by other investigators,[5,9,10] included in Table I, are seen to be in reasonable agreement. No improvement in fit was obtained when a $P_4(\cos\theta)$ term in the angular distribution of the 9.17-MeV γ ray was included. The value obtained for A_4/A_0 was -0.002 ± 0.005. A preliminary observation[14] had indicated an apparent small but definite P_4 term in the angular distribution, but the present observations, obtained with considerably improved statics, do not justify its inclusion. The statistical errors of the points are quite small and the indicated errors are standard deviations based on errors arising from the uncertainties in the shape of the tail of the 9.17-MeV γ ray and in the division of the remaining area into the three γ rays. The indicated error in the case of the 9.17-MeV γ ray arises from the integration of the area and the possibility of small shifts in the bias of the monitor counter. The least-squares fits were calculated on an IBM 650 using the method suggested by Rose.[15] The indicated errors are standard deviations based on the errors of the points.

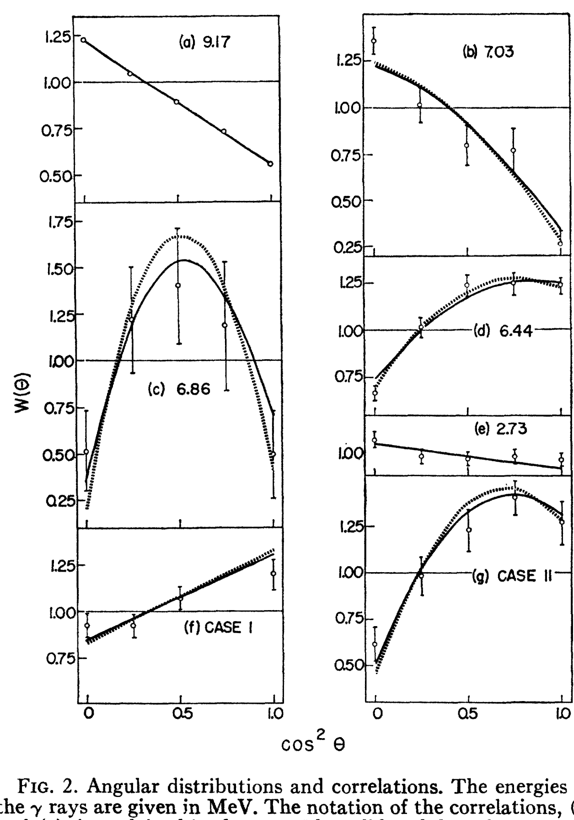

FIG. 2. Angular distributions and correlations. The energies of the γ rays are given in MeV. The notation of the correlations, (f) and (g), is explained in the text. The solid and dotted curves are the theoretical curves corresponding to the amplitude ratios, sets A and B, respectively, given in Table III and have been corrected for finite solid angle. In (a) the two curves are indistinguishable and in (e) the curve is the least-squares fit to the data.

The intensities of the transitions relative to that of the 9.17-MeV transition are given in Table II. The errors indicated are standard deviations based on the least-squares fit of the distributions and an estimated 20% error in the correction for relative detection efficiency. It can be seen that the agreement with the values obtained by Rose[5] is excellent. The slightly higher value obtained for the 6.44-MeV transition results from the presence of a negative $P_4(\cos\theta)$ term in the angular distribution and the fact that Rose used observations at 0° and 90° only and assumed a $\cos^2\theta$ distribution in calculating intensities. This same effect undoubtedly accounts for the absence of the 6.86-MeV γ ray in his proposed decay scheme.

In general, no attempt was made to extend the analysis of the spectra to lower energy γ rays than the 6.44-MeV transition because of the increased inaccuracies arising from uncertainties in the shape of the Compton tail of the more energetic γ rays. An exception was made in the case of the 2.73-MeV γ ray which results primarily from the transition to the 6.44-MeV state. Here the full energy peak is well isolated and sufficiently intense (see Fig. 1) that errors caused by uncertainties in the assumed tail on which it stands are small. Its angular distribution has therefore been included in Fig. 2(e) and in Table I and its relative intensity in Table II. Another low-energy transition of interest is the 2.14-MeV γ ray leading to the 7.03-MeV

[14] A. A. Strassenburg, R. E. Hubert, R. W. Krone, and F. W. Prosser, Jr., Bull. Am. Phys. Soc. 3, 372 (1958).
[15] M. E. Rose, Phys. Rev. 91, 610 (1953).

TABLE I. Least-squares fits to the angular distributions and correlations shown in Fig. 2. Errors indicated are standard deviations derived from the least-squares fits. Previous values are given for comparison.

γ-ray energy or correlation geometry	Present values		$W(\theta)$[a] Rose[b]	Previous values Segel *et al.*[c]	
	A_2	A_4	A	a_2	a_4
9.17	−0.44±0.01		−0.55±0.02	−0.59±0.03(−0.46)	+0.03±0.03(+0.01)
7.03	−0.68±0.09	−0.03±0.10	<−0.35		
6.86	+0.32±0.25	−0.84±0.35			
6.44	+0.48±0.05	−0.25±0.06	+0.61±0.32	+1.6 ±0.4(+0.33)	+1.1 ±0.4(−0.19)
2.73(+2.79)[b]	−0.06±0.04		−0.02±0.15	−0.14±0.05(−0.10)	
2.14	+0.5 ±0.2[d]		>0		
Case I[e]	+0.20±0.08		+0.36±0.20[f]		
Case II	+0.59±0.11	−0.28±0.13			

[a] $W(\theta)=1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)$ or $1+a_2\cos^2\theta+a_4\cos^4\theta$.
[b] See reference 5. The value given is the asymmetry $A=W(0)/W(90)-1$.
[c] See reference 10. The values of A_2 and A_4 calculated from the a_2 and a_4 given are shown in parentheses.
[d] Estimated from the asymmetry. See text.
[e] See reference 16 and text.
[f] See reference 9.

state. Unfortunately, the presence of the single escape peak and Compton edge of the 2.73-MeV γ ray and the full energy peak of the 2.31-MeV γ ray from the decay of the first excited state of N^{14} partially obscure the 2.14-MeV γ ray and render its analysis subject to large error. Inspection of the pulse-height spectra indicates that it does have a definite positive asymmetry ($A\approx 1$), which, assuming an essentially pure dipole transition, corresponds to the distribution given in Table I.

The angular correlations obtained are shown in Figs. 2(f) and (g) and the least-squares fits are given in Table I. Case I, in the terminology of Ferguson and Rutledge,[16] consists of the observation of the first γ ray, the 2.73-MeV transition, in the movable counter at $\phi=0°$ and the second, the 6.44-MeV transition, in the counter fixed at $\theta=90°$, $\phi=180°$. Case II reverses the two γ rays. Case IV, where the first γ ray is observed at $\theta=0°$, was also investigated, but proved to provide no limitations on the mixing parameters; it was, however, consistent with the choice $J=2$ for the 9.17-MeV state, $J=3$ for the 6.44-MeV state, and essentially pure dipole radiation for the 2.73-MeV transition.

DISCUSSION

The presence of $P_4(\cos\theta)$ in the angular distribution of the 6.44-MeV γ ray and the strength of the transition to the ground state uniquely determine the spin of the 9.17-MeV state as $J=2$. Its parity has been determined to be the same as that of the ground state and is therefore positive.[14] The spin of the 6.44-MeV state has previously been shown to be $J=3$ and the positive asymmetry of the 2.14-MeV transition to the 7.03-MeV state, confirmed in the present work, together with the $J=2$ spin assignment of the 9.17-MeV state uniquely determine its spin as also $J=2$.[5] The strength of the transition to the ground state from the 9.17-MeV state indicates that this state has isotopic spin $T=1$, while the same argument then establishes that the isotopic spins of the 7.03- and 6.44-MeV states are both $T=0$. These assignments are indicated in Fig. 3. (Only the levels in N^{14} relevant to the present discussion are shown.)

A thorough examination of alternate spin assignments has been made for the data shown in Fig. 2 and no other set appears compatible for reasonable values of the amplitude ratios. This conclusion is in agreemen' with that of earlier work.[9] Therefore the analysis presented here will deal with the assignment of the partial width and amplitude ratios and a comparison of the results to the predictions of WP.

The theoretical angular distributions were calculated from the tables of Sharp *et al.*[17] with the correction of Huby,[18] and the correlations from the tables of Ferguson and Rutledge.[16] They are shown in Fig. 4, plotted as a function of the ratio of amplitudes f/p for formation of the compound state. A channel radius of 3.72×10^{-13} cm. was assumed. With this radius, the term [19] $\cos(\xi_1-\xi_3)$ which enters the terms in the theoretical distributions linear in the orbital angular momentum amplitude ratio

TABLE II. Relative intensities of observed transitions. Errors indicated are standard deviations derived from the least-squares fits and the estimated error in the correction for relative detection efficiency.

γ-ray energy	Relative intensity Present investigation	Previous work[a]
9.17[b]	100	100
7.03	4.4±0.6	3±1
6.86	1.4±0.5	c
6.44	7.8±0.5	7±2
2.73(+2.79)[a]	12.6±1.0	12±2

[a] See reference 5.
[b] Normalization standard for intensities.
[c] Not observed.

[16] A. J. Ferguson and A. R. Rutledge, Atomic Energy of Canada, Ltd., AECL-420, 1957 (unpublished).

[17] W. T. Sharp, J. M. Kennedy, B. J. Sears, and M. G. Hoyle, Atomic Energy of Canada, Ltd., AECL-97, 1954 (unpublished).
[18] R. Huby, Proc. Phys. Soc. (London) **67**, 1103 (1954).
[19] J. M. Blatt and L. C. Biedenharn, Rev. Mod. Phys. **24**, 258 (1952).

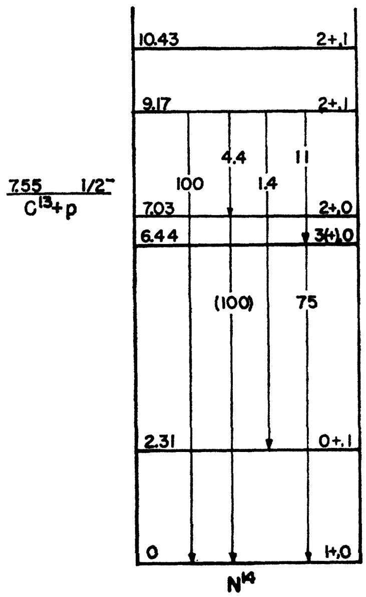

FIG. 3. Energy level diagram of N^{14}. Only those levels relevant to the present discussion are included. Intensities of the γ rays from the 9.17-MeV state are normalized to 100 for the transition to the ground state; those from the 6.44- and 7.03-MeV states are based on a total of 100. Tentative assignments are given in parentheses. Transitions to other states, discussed by Rose (reference 5), have not been shown.

was calculated to be 0.860.[20] In the case of the 9.17-MeV transition several curves are shown corresponding to the indicated amplitude ratios of quadrupole radiation. Similarly, in the case of the 7.03-MeV γ ray, the several curves correspond to the indicated amplitude ratios of quadrupole to dipole radiation in the transition from the 7.03-MeV state. The results are insensitive to the choice of the small amount of quadrupole radiation which may be present in the 2.14- and 2.73-MeV transitions. The 6.86-MeV transition must be pure quadrupole.

The results have been corrected for the finite geometry of the detectors by the method of Rose.[15,21] In the case of the angular distributions, this was done by correcting the experimental least-squares fits to the values shown in Fig. 4 for comparison to theory. In the case of the angular correlations, the theoretical expressions were corrected for finite geometry. The method of Rowe *et al.*[22] can be extended to the case of $(p,\gamma\gamma)$ correlations, and it can be shown[23] that the expression for the angular correlation between successive γ-ray transitions following particle capture, corrected for finite geometry of the detectors, can be written

$$W(\theta_{12},\theta_2,\phi)_{tt'}=\sum_{KMN} D_{KM}{}^N(tt')X_{KM}{}^N(\theta_{12},\theta_2,\phi)J_KJ_M,$$

where

$$X_{KM}{}^N=f(K,M,N)P_K{}^N(\theta_{12})P_M{}^N(\theta_2)\cos N\phi.$$

Here the notation for the correlation is that of Ferguson and Rutledge[16] and the correction for finite geometry, J_l, that of Rose.[15] It is apparent, with the expression in this form, that Rose's theorem that finite geometry does not increase the complexity nor mix terms is still valid.

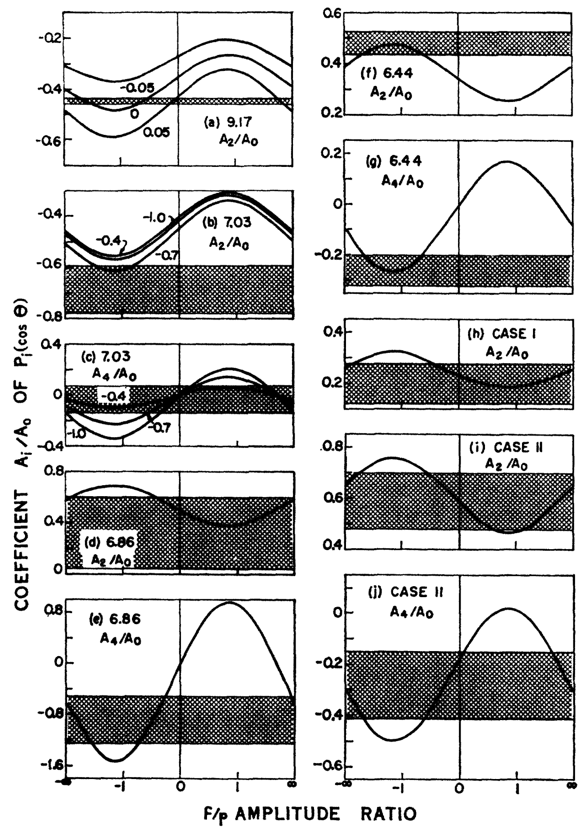

FIG. 4. Theoretical coefficients for the measured angular distributions and correlations, plotted as a function of the amplitude ratio, f/p, for formation of the compound state. The cross-hatched areas are those values within one standard deviation of the least-squares value of that coefficient. The curves in (a), (b), and (c) are labeled by the amplitude ratio, $E2/M1$, in the 9.17-, 7.03-, and 7.03-MeV γ rays, respectively. The abscissa scale is the arctangent of the f/p amplitude ratio. The experimental values for the angular distributions are corrected for finite geometry, as are the theoretical values for the angular correlations, as explained in the text.

[20] W. T. Sharp, H. E. Gove, and E. B. Paul, Atomic Energy of Canada, Ltd., AECL-268, 1955 (unpublished).

[21] It has been pointed out by several investigators that the integrals J_l introduced by Rose (reference 15) for the correction of angular distribution data for finite solid angles are strictly correct only if the entire spectrum produced by the γ ray is included and represents only an upper limit on the correction if, as here, only a portion of the spectrum is used [see, e.g., C. R. Gossett and C. M. Davisson, Naval Research Laboratory Quarterly Report, 1961 (unpublished)]. This effect is negligible for the angular distributions here because of the small solid angle used. While the effect is larger for the correlation data, the size of the statistical uncertainties did not seem to warrant the much more difficult analysis required.

[22] D. J. Rowe, G. L. Salmon, and A. B. Clegg, Nucl. Instr. Methods 12, 353 (1961).

[23] D. S. Ling, Jr., and F. W. Prosser, Jr. (to be submitted to Nucl. Phys.)

If, however, the fixed angles are chosen conveniently and the expression reduced to the usual form[16]

$$W_{tt'}=\sum_r A_r P_r(\cos\beta),$$

where β is the remaining variable angle, and now

$$A_r=\sum_{KMN}\alpha_{rKM}{}^N D_{KM}{}^N(tt')J_K J_M,$$

it is apparent that the correction of the rth term by multiplication by $(J_r)^2$ is not correct. Since angular correlations are often measured in poor geometry, this difference may frequently be significant. Moreover, since terms in the sum may be either positive or negative, it is possible for the finite geometry correction to actually increase the magnitude of a particular term A_r or to remove an accidental cancellation and hence increase the apparent complexity of the correlation when expressed in the final, usual form. An example of this effect may be seen in Fig. 4(j) in the region where A_4/A_0 becomes positive. Without the solid angle correction, this coefficient is positive over a shorter region and remains smaller in magnitude in this region.

From Fig. 4 it can be seen that, regardless of the choice of multipole mixing assumed for the 7.03-MeV transition, no single value of the ratio f/p allows a fit of all of the angular information within one standard deviation of the least-squares values. However, if this requirement is relaxed slightly, a value for this ratio of about −0.5 will allow a fit of all data well within 1.5 standard deviations. Best values of the amplitude ratios were calculated in two ways, a first set which used all of the data and a second which did not include the correlation data. These values are given in Table III and were used to determine the curves shown in Fig. 2. It can be seen that the two sets are compatible, both with themselves and, in magnitude, with previous measurements, and that they provide satisfactory fits to the angular distributions. The second set is regarded as somewhat more reliable for two reasons. First, the errors stated on the angular correlation data are purely statistical and do not include the possibility of small contributions from other cascades. Second, and more importantly, the correlations are sensitive to the amplitude of a possible quadrupole contribution to the 2.73-MeV transition. An amplitude ratio of quadrupole-to-dipole radiation of from +0.05 to +0.1 allows an improved fit of all three coefficients obtained in the correlations. These are not unreasonably large if the 6.44-MeV state has positive parity, particularly if there is collective enhancement of the $E2$ transition probability. There remains the possibility that the 6.44-MeV state has negative parity and that quadrupole-octupole mixing occurs in the ground-state transition. This would affect not only the correlations but also the distribution of the 6.44-MeV γ rays and the sign of the mixing parameter which improves the fit of some terms has the opposite effect on others. These arguments, together with the fact that all the expected negative parity states in this region of excitation are believed to be identified,[4] tend to support a positive parity assignment for the 6.44-MeV state.

TABLE III. Best values of amplitude ratios. Set A was calculated with the angular correlation data included; set B was not. Values obtained by others have been included for comparison.

Transition and mixing considered	Amplitude ratio Set A	Set B	Previous work
Formation of compound state, f/p	−0.43 ±0.18	−0.70 ±0.26	$+0.3<\delta<+0.8$[a]
9.17 to ground state, $E2/M1$	+0.01 ±0.02	−0.005 ±0.020	$-0.02<\delta<0$[a]
7.03 to ground state, $E2/M1$	−0.65 ±0.15	−0.60 ±0.10	$+0.13<\delta<+3.5$[b]

[a] See reference 10.
[b] See reference 5. While neither Rose nor Segel *et al.* state the phase convention used in deducing the relative signs of the amplitudes, the agreement of the data and the magnitude of the amplitude ratios suggests that their computations were made without the Huby correction.

TABLE IV. Experimental and predicted values of the partial widths, Γ_γ, and amplitude ratios, $E2/M1$, for several of the observed transitions. The predicted values have been calculated from the reduced transition amplitudes given by WP on the basis of the γ-ray energies of the transitions and the assumption of collective enhancement of $E2$ transitions when $\Delta T=0$.

γ-ray energy (MeV)	Partial widths (eV) Experimental	Predicted	Amplitude ratios Experimental	Predicted
9.17	8.7[a]	27	−0.005±0.020	+0.035
7.03	b	0.14	−0.60 ±0.10	+0.57
6.86	0.12±0.04	0.069	∞[c]	∞[c]
2.73	0.96±0.17	1.84	$0\leq\delta<+0.1$	d
2.14[e]	0.38±0.05	0.51	d	−0.005

[a] Normalization standard for partial widths. See reference 24.
[b] Undetermined.
[c] Quadrupole radiation required for 2 → 0 transition.
[d] Undetermined, but assumed small.
[e] Partial width calculated from intensity of 7.03-MeV γ ray. Predicted branching is less than 1%.

The large quadrupole/dipole ratio required to fit the 7.03-MeV angular distribution is in good agreement with the prediction of WP for the decay of the (2+, 0) state to the (1+, 0) ground state and confirms Rose's identification of that state.[5] The angular distribution predicted for the 2.14-MeV transition to that state, assuming dipole radiation and an f/p ratio of −0.70, is $1+0.46P_2(\cos\theta)$, in excellent agreement with the measured asymmetry.

As pointed out by Rose,[5] the presence of a weak 2.79-MeV γ ray with an expected strong angular distribution under the peak of the 2.73-MeV γ ray renders an analysis of its angular distribution of little value in the determination of the mixing parameters.

In Table IV the experimentally determined partial widths, based on the value $\Gamma_\gamma=8.7$ eV for the 9.17 → ground-state transition,[24] and amplitude ratios for $E2/M1$ radiation are compared to those calculated by

[24] S. S. Hanna and L. Meyer-Schützmeister, Phys. Rev. **115**, 986 (1959).

TABLE V. Proton widths of the 9.17-MeV state. The partial widths are based on the value 77±12 eV for the total width from Hanna and Meyer-Schützmeister.[a] The reduced widths $\theta_p(l)^2$ are expressed in units of $3(T_i\frac{1}{2}T_{zi}-\frac{1}{2}|T_fT_{zf})^2\hbar^2/2mR$ (see WP) and a radius of 3.72 F was used. The predicted value of $\theta_p(1)^2$ was calculated by WP assuming a (p^{-2}) configuration of the 9.17-MeV state.

l	Γ_{pl}(eV)	$\theta_p(l)^2$ Experimental	$\theta_p(l)^2$ Predicted
1	44±13	$(6.3\pm1.8)\times10^{-5}$	1.9×10^{-2}
3	22±11	$(8.1\pm4.1)\times10^{-4}$	

[a] See reference 24.

WP from the wave functions of Visscher and Ferrell[3] and of Redlich.[25] A collective enhancement to the intensity by a factor 5.2 has been assumed for all $\Delta T=0$ $E2$ transitions.[4] The prediction of the intensity of the 2.73-MeV transition to the 6.44-MeV state is based on the assumption that the wave function of the 9.17-MeV state arises entirely from the $p^8(s,d)$ configuration; all other calculations assume that it arises entirely from the (p^{-2}) configuration. As mentioned above, there appears reason to believe that both the 9.17- and 10.43-MeV states share a mixture of these configurations. The relative strength of the 2.73-MeV transition has been reduced from that given in Table II by 2+1% of the 9.17-MeV γ ray to account for the presence of the 2.79-MeV γ ray.[5] The agreement in general is good, although most of the measured widths are smaller, as expected from the mixture of configurations. The reversal in sign of the amplitude ratios is believed to result from a difference in phase conventions. The agreement between the measured and predicted widths for the 6.86-MeV transitions to the (0+, 1) first excited state is of significance in confirming the positive parity assignment to the 9.17-MeV state since the width for an $M2$ transition of this energy would be at least a factor of 20 smaller, in complete disagreement with the present experimental results. The partial widths and reduced widths for f- and p-wave formation of the compound state are given in Table V. Here a total proton width of 66±12 eV has been calculated from the value 77±12 eV for the total width of the 9.17-MeV state.[24]

CONCLUSIONS

The evidence from the partial widths, Γ_γ, of the decay of the 9.17-MeV state to the ground, 2.31-MeV, and 7.03-MeV states and the $E2/M1$ amplitude ratio in the decay of the 7.03-MeV state confirms the configuration assignments given these states by WP and Rose.[5] As has been pointed out by WP, the reduction of the proton width of the 9.17-MeV state can be explained by assuming that it consists of a mixture of the (p^{-2}) and $p^8(s,d)$ configurations, with amplitudes $(1/3)^{1/2}$ and $(2/3)^{1/2}$, respectively, and that the ground state of C^{13} is contaminated by a configuration of the form $p^7(s,d)$ to the extent of about 0.2 in amplitude. This has the advantage of simultaneously explaining the reduction of about two-thirds in the radiation widths of the decays to the ground and 7.03-MeV states. These assumptions, however, do not explain the reduction of the $E2/M1$ amplitude ratio of the 9.17-MeV γ ray, the enhancement of the 6.86-MeV γ ray, and the presence of an appreciable f-wave proton width for the 9.17-MeV state.

Perhaps the most tempting explanation for these effects is that proposed by Segel *et al.*,[10] who have suggested that the contaminant of the (p^{-2}) configuration of the 9.17-MeV state is $(pf;J=2,T=1)$. If this assignment is coupled with the possibility suggested by WP of assigning the configuration $(p_{1/2}f_{7/2})$ to the 6.44-MeV state, a number of difficulties can be removed. Such an explanation would certainly account for the presence of the f-wave proton width of the 9.17-MeV state. The decrease of the $E2$ transition probability in the ground-state transition and its increase in the transition to the first excited state could result from interference between the $(p^{-2})\rightarrow(p^{-2})$ and $(pf)\rightarrow(p^{-2})$ amplitudes in these decays. Similarly the large $M1$ transition probability for the transition to the 6.44-MeV state could be retained and the large cross section for the $N^{14}(\alpha,\alpha')$ reaction leading to the 6.44-MeV state[12] would be understandable. There are, however, two difficulties with this conjecture. First and most serious would be the failure of such a configuration for the 9.17-MeV state to produce the necessary cancellation of the p-wave proton width without assuming an unreasonably large contamination of the C^{13} ground state by an $f_{7/2}$ admixture. Second, as pointed out by WP, the lowest states resulting from the excitation of a single particle into the $f_{7/2}$ shell should occur at about 9 MeV rather than at 6.5 MeV. A (2+, 1) state from this configuration, presumably resulting from the addition of an $f_{7/2}$ nucleon to the second excited, $3/2^-$, state of C^{13}, can be estimated to occur only above about an excitation of 13 MeV. In any case, the reduced width for f-wave protons is still well below single-particle values and can probably be accounted for by abandoning extreme j-j coupling in the calculations or requiring at most insignificant contaminations of the states in question.

Existing evidence does not rule out the possibility of a negative parity assignment for the 6.44-MeV state, although the present work slightly favors a positive parity. In such a case WP suggest the configuration $(pd;J=3)$ based on the $3/2^-$ state of C^{13}, although, again, such a state should occur at about 9 MeV. However, it is then difficult to understand the strong transition to it from the 9.17-MeV state[4] and the absence of a strong transition from it to the 5.10-MeV state as occurs from the very similar state at 5.83 MeV.

It appears that still more information is needed about the properties of the 6.44-MeV state before the character of the 9.17-MeV state can be completely understood.

[25] M. G. Redlich, Phys. Rev. **110**, 468 (1958).